AN EXPERIMENTAL INVESTIGATION OF THE NONLINEAR RESPONSE OF THIN-WALLED FERROMAGNETIC SHIELDS TO SHORT-DURATION CURRENT PULSES

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ABSTRACT

Intense electromagnetic (EM) fields can disrupt, disable, damage, or destroy sensitive electronic equipment that is needed to perform critical functions such as those related to command, control, communications, computer, intelligence, surveillance, and reconnaissance (C^4ISR). EM shielding is used to protect equipment against such detrimental effects to promote the survivability of mission critical systems. Ferromagnetic materials can have a high magnetic permeability, which may be a significant advantage in shielding applications; however, the permeability varies with applied magnetic field intensity. An understanding of the performance of ferromagnetic shields under intense transient field conditions is needed to design a shield to attenuate fields to an acceptable level, to predict the performance of a given shield, or to determine the level of EM fields that would defeat a given shield and induce unacceptable EM field levels. This paper presents the results of an experimental investigation of the nonlinear response of thin-walled ferromagnetic shields to short-duration surface current pulses. The results provide an improved understanding of the performance of ferromagnetic shields under intense transient EM field conditions.

1. INTRODUCTION

EM shielding is accomplished by interposing an electrically conductive (e.g., metallic) material between the source of an EM disturbance and the volume to be protected. The purpose of the EM shield is to attenuate the EM fields from the threat level to an acceptable level. The performance of an EM shield in a given application depends on the characteristics of the EM threat (e.g., amplitude and time variation), the material properties of the shield (electrical conductivity, σ, and the magnetic permeability, μ) and the geometry (e.g., shape and thickness) of the shield. The optimization of an EM shield design requires a quantitative understanding of the interrelationships among the various parameters.

Generally, a high value for the magnetic permeability is desired. Ferromagnetic materials offer potential advantages in shielding applications, especially where weight and size limitations are important. On the other hand, the magnetic permeability of ferromagnetic materials is field-dependent. Due to the field dependent permeability, ferromagnetic materials exhibit nonlinear behavior including magnetic saturation when exposed to high field levels. Consequently, it is difficult to predict the shield performance, especially under pulsed EM field conditions.

As the applied magnetic field is increased from zero, the magnetic permeability typically starts at an initial value, increases to a maximum value, and then decreases to the permeability of free space, μ_0, as the material undergoes magnetic saturation. As a result of the field-dependent permeability, the penetration of electromagnetic fields into ferromagnetic shields is inherently a nonlinear phenomenon, which makes it difficult to predict the performance of ferromagnetic shields under intense transient field conditions. An understanding of the behavior of ferromagnetic materials under intense transient EM field conditions is needed to support the development of new design and evaluation procedures and to enable the optimization of material properties.

This paper considers the fundamental problem of a long, electrically conductive ferromagnetic cylinder subjected to a surface current pulse. The fields associated with the applied pulse diffuse into the shield and induce a transient electric field or diffusion signal at the interior surface. The maximum value of the electric field transient, and the time at which the maximum value occurs, are of primary interest. The emphasis of the study is on the nonlinear nature of this transient electric field response.

Some results of theoretical and numerical investigations for a planar approximation to the above cylindrical problem were reported previously (Croisant et al., 1994; Croisant et al., 1996; Croisant et al., 2002a; Croisant et al., 2002b; Croisant et al., 2003). The theoretical results indicated that an applied pulse of sufficiently short duration could be regarded as an impulse and the electric field response as an impulse response. This study considers the results of an experimental investigation of the problem to confirm the theoretical predictions of a nonlinear impulse response for short duration pulses. Preliminary results were reported previously (Croisant et al., 2004). The present paper offers additional analysis and interpretation. In the experiment described below, a thin-walled, cylindrical, electrically conductive ferromagnetic specimen was subjected to a wide range of injected current pulses.

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The first objective of the experiment was to investigate experimentally the transient electric field response as the duration of the applied current pulses was made shorter while maintaining the total charge injected during the applied pulse at the same level. For an applied current pulse with a duration that was long compared to the response time for the shield, the transient electric field response was observed to be strongly dependent on the time variation of the applied pulse. However, as the applied pulse was made shorter while maintaining the total injected charge constant, the transient electric field response became less and less dependent on the time variation of the applied pulse. For applied pulses with a duration that was sufficiently short compared with the response time for the shield, the transient electric field responses approached a result that depended on the total charge transported along the surface of the cylinder during the applied current pulse but was essentially independent of the particular variation of the applied pulses. For practical purposes, such pulses can be regarded as impulses, and the resultant electric field response can be regarded as an impulse response. While an impulse response is well known in linear problems with a constant permeability, the existence of an impulse response for a nonlinear problem is not immediately obvious because higher amplitude pulses might be expected to drive the shield farther into saturation than lower amplitude pulses. Therefore, the total charge injected during the applied pulse is a better measure of the severity of an applied pulse than the amplitude alone.

The second objective of this experiment was to investigate the transient electric field response for different pulse levels while maintaining the same pulse shape (time variation) of the short-duration applied pulses. Experimental results for a wide range of injected charge levels for a mildly ferromagnetic specimen are presented.

A third objective of this study was to investigate the nonlinearity of the phenomenon by examining the ratio of the peak response to the injected charge versus injected charge. Unlike the impulse response for the linear case with a constant permeability, the results for the nonlinear case with a field dependent permeability are found to vary with the injected charge level. The ratio of the injected charge to the peak response versus injected charge is also considered.

2. PROBLEM DESCRIPTION

This study considers a thin-walled, cylindrical, electrically conductive ferromagnetic shield subjected to axially directed, unipolar, short-duration current pulses injected uniformly along the exterior surface as shown in Fig. 1. This configuration has application to cable shields and conduit-protected wires.
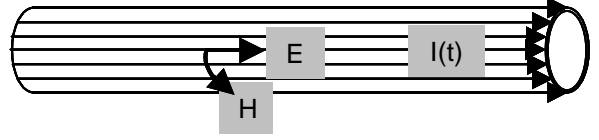

Fig. 1: A cylinder subjected to an axially directed surface current pulse.

The pulses considered here are unipolar pulses of the form

$$I(t) = A\left[\exp\left(-\frac{t}{t_f} \right) - \exp\left(-\frac{t}{t_r} \right) \right] \qquad (1)$$

where A is an amplitude factor, t_r is a time constant associated with the rise time, and t_f is a time constant associated with the fall time. This idealized pulse shape is shown in Fig. 2.
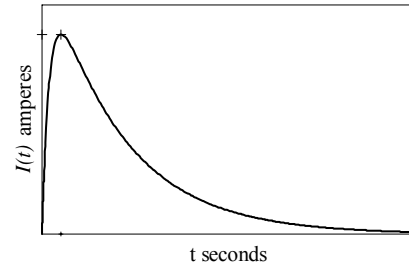

Fig. 2: Idealized applied current pulse, $I(t)$.

This generic pulse shape can be used to represent a variety of physical phenomena such as electromagnetic pulse (EMP), electrostatic discharge (ESD), and lightning depending on the values selected for the amplitude and time constants.

By definition, the total charge injected during a pulse is expressed as

$$Q = \int_0^\infty I(t)dt \qquad (2)$$

For a pulse of the form (1), the total charge is

$$Q = A\left(t_f - t_r \right) \qquad (3)$$

As the fields associated with an applied pulse diffuse into the shield, a transient electric field is induced at the inner surface. It is this transient electric field response that is of concern. An idealized electric field response, $E(t)$, is shown in Fig. 3. The response starts from zero gradually, increases to a maximum value, and then decays to zero. The peak is delayed due to diffusion through the shield

wall. The peak value, E_{peak}, and the time at which the peak value occurs, t_{peak}, are of primary interest.
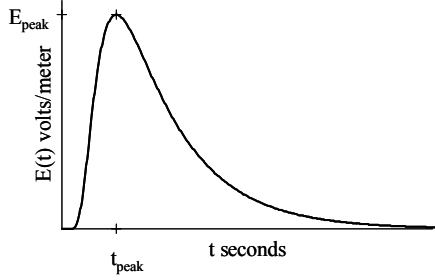

Fig. 3: Idealized electric field response, $E(t)$.

3. EXPERIMENTAL SETUP

The specimen under test was subjected to injected current pulses generated by capacitor discharge using the experimental setup shown in Fig. 4.
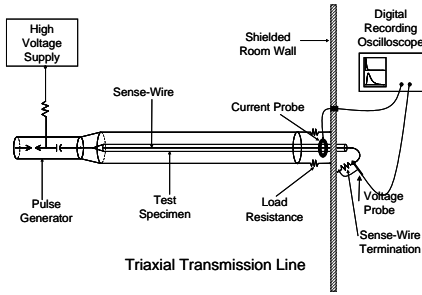

Fig. 4: Experimental setup for injected current tests.

The specimen under test was inserted as the center conductor in a coaxial transmission line configuration, which in turn was enclosed within a shielded room. One end of the cylinder was enclosed by an end-cap to which a sense-wire was attached to the inside. The other end of the specimen was connected to a conduit stub that penetrated the wall of the shielded room such that the sense-wire extended through the wall to allow measurements to be made outside of the shielded room. A cylindrical shroud was placed around the test specimen to form a coaxial transmission line that was terminated by a load resistor. A capacitor discharge pulse generator was used to generate short-duration pulses, which were injected onto the end-cap of the cylindrical specimen and passed along the test specimen, through the load resistor, and back to the pulser via the shroud.

The pulse generator consisted of a fixed capacitor, C, and an adjustable spark gap that was used to set the maximum voltage for the applied pulse, V_g. The capacitor and spark gap were located in a housing pressurized with sulfur hexafluoride (SF_6) gas. The firing voltage for the spark

gap, V_g, was determined by the SF_6 gas pressure and the gap spacing. When the charging voltage reached V_g, the spark gap fired and the capacitor, C, was discharged along the specimen and through the load resistor, R.

A current probe was used to measure the actual current pulse injected onto the test specimen. The applied current pulse was integrated to determine the charge transported during the pulse. The integration was performed numerically using a digital recording oscilloscope and software. A conversion factor was applied to convert the integrated result to coulombs.

The sense-wire attached to the inside of the end-cap was used to monitor the induced voltage. The sense-wire was connected to the exterior wall of the shielded room by a 56Ω termination resistor, which was large enough to approximate an open circuit for the diffusion signal.

The test setup conveniently allowed the generation of pulses with different amplitudes and time constants, but approximately the same value of charge, by changing the value of the load resistance, R, while maintaining the firing voltage V_g constant. The value V_g was controlled by adjusting the spacing between the electrodes in the spark gap. For a fixed V_g, the amplitude and time variation of the applied current pulse were modified by changing the value of R by substituting resistors. This method allowed the generation of applied pulses with different amplitudes and time constants while maintaining approximately the same value for Q. Because the value of C in the pulse generator was fixed, the maximum charge that could be injected was

$$Q = CV_g \qquad (4)$$

While the early time characteristics of the applied pulse (especially the rise time) were affected by the transmission line properties of the test configuration, the long time characteristics of the applied pulse were essentially those of capacitor discharge in an RC circuit and were determined primarily by the voltage, V_g, the capacitor, C, and the load resistor, R. For an RC circuit,

$$I(t) = \frac{V_g}{R} \exp\left(-\frac{t}{RC}\right) \qquad (5)$$

From (2) and (5),(4) can be rewritten as

$$Q = \int_0^\infty I(t)dt = -CV_g \exp\left(-\frac{t}{RC}\right)\Bigg|_0^\infty = CV_g \qquad (6)$$

4. EXPERIMENTAL RESULTS

For the results presented here, the pulser had a fixed capacitance C=0.02 microfarad and could generate pulses

with voltages in the range $0<V_g<5\times10^4$ volts, so the maximum charge that could be stored in the capacitor and injected onto the specimen was about $Q=1\times10^{-3}$ coulomb.

To investigate the effects of applied pulse duration on the shield response, the ferromagnetic specimen was subjected to a sequence of pulses using several values of R, which were changed while maintaining V_g constant. The nominal values of load resistance used in the test sequence were: 250Ω, 125Ω, 50Ω, 25Ω, and 17Ω for which the nominal RC time constants were $5.0\mu s$, $2.5\mu s$, $1.0\mu s$, $0.5\mu s$, and $0.34\mu s$ respectively. The maximum possible amplitudes were $2.0\times10^2 A$, $4.0\times10^2 A$, $1.0\times10^3 A$, $2.0\times10^3 A$, and $2.5\times10^3 A$, respectively. As the value of R was reduced from the highest value, the applied pulse had a larger amplitude, but a shorter duration. This procedure was repeated for selected voltages in the range $0<V_g<5\times10^4 V$. At each pulse setting, the signals were averaged over 32 pulses by the digital oscilloscope.

The sense-wire open circuit voltage is proportional to the electric field and the length of the specimen. An idealized voltage response, $V_s(t)$, is shown in Fig. 5 to illustrate the quantities of primary interest: the peak value, V_{peak} and the time at which the peak value occurs, t_{peak}.
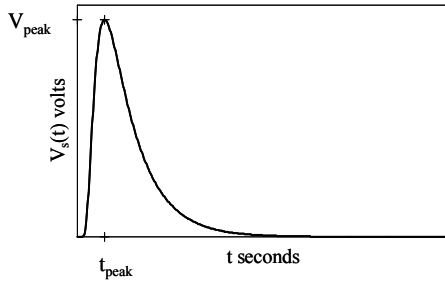

Fig. 5: An idealized sense-wire voltage response $V_s(t)$.

To illustrate the procedure, some results from pulse tests on a low-carbon steel foil specimen are presented here. The cylindrical specimen was fabricated from ferromagnetic foil wrapped over a non-conducting mandrel for physical support. The foil was a mild 1010 steel, with No. 1 temper that complies with Federal Specification QQ-S-698 (USGPO, 1984). The thickness of the foil was nominally 1 mil (0.001 inch). The inside diameter of the ferromagnetic specimen was nominally ¼ inch, or 6.48×10^{-3} meter (0.255 inch). Wall thickness was approximately 1.9×10^{-4} meter (0.0075 inch). The outer diameter was approximately 6.86×10^{-3} meter (0.270 inch). The length of the specimen was 1.83 meter (72 inches).

For ease of comparison, the results are presented in terms of the voltage response measured on the sense-wire since the objective of this study was to investigate the nonlinear nature of the impulse response rather than the

absolute value of the electric field. The electric field can be estimated by dividing the measured voltage response by the length of the specimen exposed to the pulse.

The test sequence for $V_m \cong 4.7\times10^4$ volts, which was the highest value used for V_g, is illustrated by the oscillographs shown in Fig. 6 for the test sequence The results are shown from the lowest-amplitude, longest-duration pulse using $R=250\Omega$ on the bottom to the largest-amplitude, shortest-duration pulse using $R=17\Omega$ on the top. As the applied pulse duration was made shorter, the voltage response tended toward a result that did not depend appreciably on the time variation of the applied pulse. The sequence was performed at other selected voltages (not presented here) and returned similar results.

It is noted that the early time behavior of the applied current pulses exhibited a burst of noise. This burst of noise at the start of the sense-wire response is believed to be due to an unidentified leakage path and not part of the diffusion signal. One component appears to be due to the initiation of discharge in the spark gap. Also, the test specimen and shroud formed a coaxial transmission line with a fixed configuration. Since the transmission line was not always terminated in its characteristic impedance, there were reflections in the early times of the current pulse.

For a second series of measurements to investigate the response for various charge levels, the resistance was fixed at $R=17\Omega$ to give the shortest-duration pulse, and the firing voltage V_g was changed by adjusting the spark gap spacing. The peak voltage of the measured response is plotted versus the injected charge in Fig. 7.

5. DISCUSSION OF RESULTS

It is important to note that the suitability of a particular applied pulse as an impulse is not an inherent property of the pulse but depends on the time variation of the applied pulse compared to the response time (t_{peak}) for the shield under consideration. Consequently, an applied pulse may be a good approximation of an impulse for one shield but may represent a long pulse for another shield. It is advisable to use an applied pulse such that several time constants have elapsed before the peak of the transient response occurs. For the results presented here, the fastest applied pulse that could be generated was marginal as an impulse for this specimen, but it was a good approximation for another specimen with a greater wall thickness and later occurrence of the peak of the transient response. While the transient voltage response was approximately invariant for pulses with the same charge, the transient voltage response did depend on the level of charge that was transported along the specimen during the applied current pulse. Thus, the value of Q is a better measure of

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the severity of the applied current pulse than the amplitude alone. Experimental results for a range of injected charge levels are presented. Fig. 7 shows the maximum values of the voltage responses plotted versus injected charge for measurements made with selected voltages in the range $0 < V_m < 5 \times 10^4$ volts, which corresponded to selected values of charge in the range $0 < Q < 1 \times 10^{-3}$ coulomb. This curve characterizes the performance of the specimen for short-duration pulses in the range $0 < Q < 1 \times 10^{-3}$ coulomb. For a constant permeability, the results would be a straight line.

The nonlinearity of the phenomenon is more evident by considering the ratio of the peak response voltage to the injected charge as shown in Fig. 8. As the applied charge is increased, the results start from a value near $Q=0$, decrease to a minimum, and then increase. For a constant permeability, this ratio would be a constant (horizontal line) with no variation.

The ratio of applied charge divided by the peak response voltage versus Q is shown in Fig. 9 (the inverse of Fig. 8). This plot provides a qualitative indication of the underlying performance of the material. As the applied charge is increased, the results start from a value near $Q=0$, then increase to a maximum, and then decrease as the material undergoes saturation. There is a value of Q for which the ratio is maximum, which indicates that there is a value of Q for which material performance is optimum. For a constant permeability material, this ratio would remain constant with no variation.

6. CONCLUSIONS

Experimental results for a ferromagnetic specimen subjected to a wide range of injected current pulses were presented. For applied current pulses with a duration that was sufficiently short relative to the internal response, the internal responses approached a result that depended on the total charge, Q, transported along the surface of the cylinder during the applied current pulse but was essentially independent of the particular time variation of the applied pulse. Thus, the value of Q is a better measure of the severity of the applied current pulse than the amplitude alone. For practical purposes, such applied pulses can be regarded as impulses, and the resultant response as an impulse response. The results of this experimental investigation confirm the predictions of the theoretical investigations conducted previously.

The impulse response allows the results for one applied pulse to be used to predict the performance of the shield for another applied pulse with the same total charge Q as long as the applied pulses are of sufficiently short duration compared with the shield response time. It is emphasized that the impulse characteristic of an applied pulse is not an inherent property of the applied pulse but

is relative to the response time of the particular shield under consideration. That is, a short-duration pulse for one shield may represent a long-duration pulse for a different shield, and vice versa. It is advisable to use an applied pulse with a duration such that several time constants have elapsed before the peak of the transient response occurs. If the applied pulse still has an appreciable level when the peak response occurs, the response is influenced by the characteristics of the applied pulse and is not an impulse response.

The maximum values of the impulse responses over a range of applied charge levels were determined for a mildly ferromagnetic specimen. These results characterize the response of the shield over the range of Q. When plotted versus Q, the results can be used to predict the response of the shield for pulses having a given Q. The results exhibit some nonlinearity and depart from the straight line behavior for a constant permeability.

The nonlinearity of the phenomenon is readily evident by considering the ratio of the peak internal response to the applied charge Q plotted versus Q. This is indicative of the field that is induced per unit charge. Unlike the impulse responses for the linear problem with a constant permeability, the impulse response exhibits nonlinear variation with Q. As the applied charge is increased from zero, the results start from a value near $Q=0$, decrease to a minimum, and then increase. Although the overall peak field level increases with increasing Q, the rate varies with Q. For a constant permeability, the results would be expected to be a flat line.

A qualitative indication of the material performance can be obtained by considering the ratio of the applied charge Q to the peak internal response. As Q is increased, the results start from an initial value near $Q=0$, increase to a maximum, and then decrease. This result indicates that there is a value for Q for which the material has optimum performance.

The results of this study provide an improved understanding of the behavior of ferromagnetic shields under intense transient field conditions generated by short-duration surface current pulses. The results have application to electromagnetic shield design and assessment.
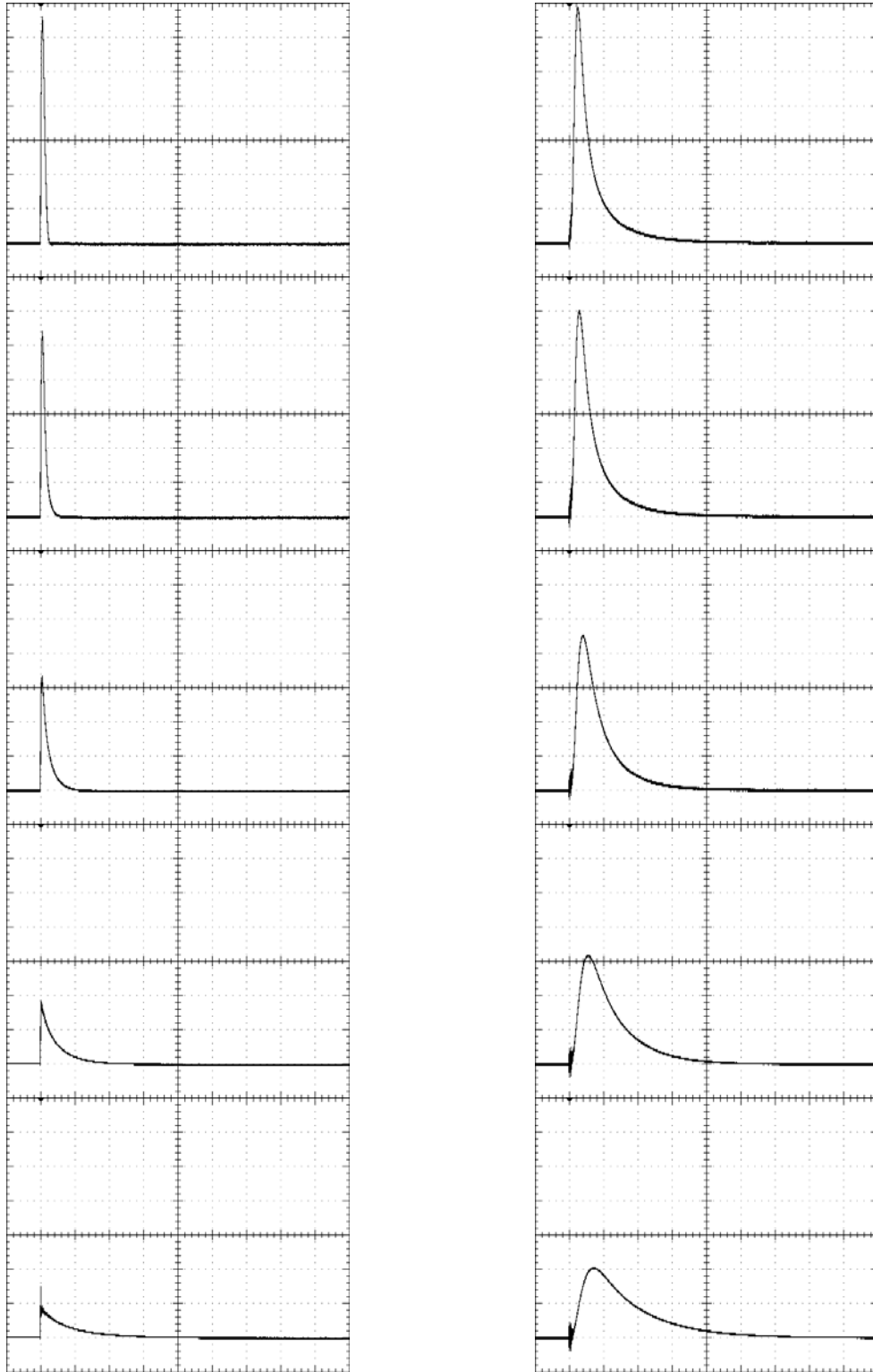
Fig. 6: Response waveforms (right column) for various drive pulses (left column). The pulser voltage was approximately 47 kV and the load resistance was varied from 250 Ω (bottom) to 17 Ω (top). The vertical scales are 300 milliamps/division and 3.4 volts/division, respectively, for the drive and response sets of plots. The horizontal scale is 4 μs/division for both sets.
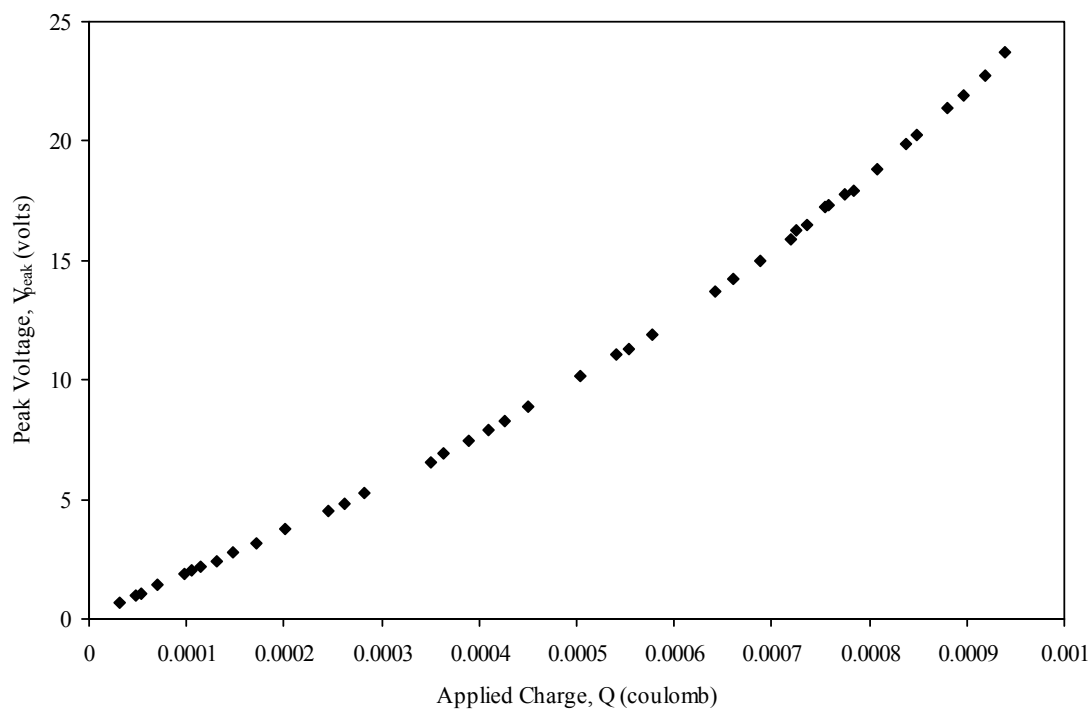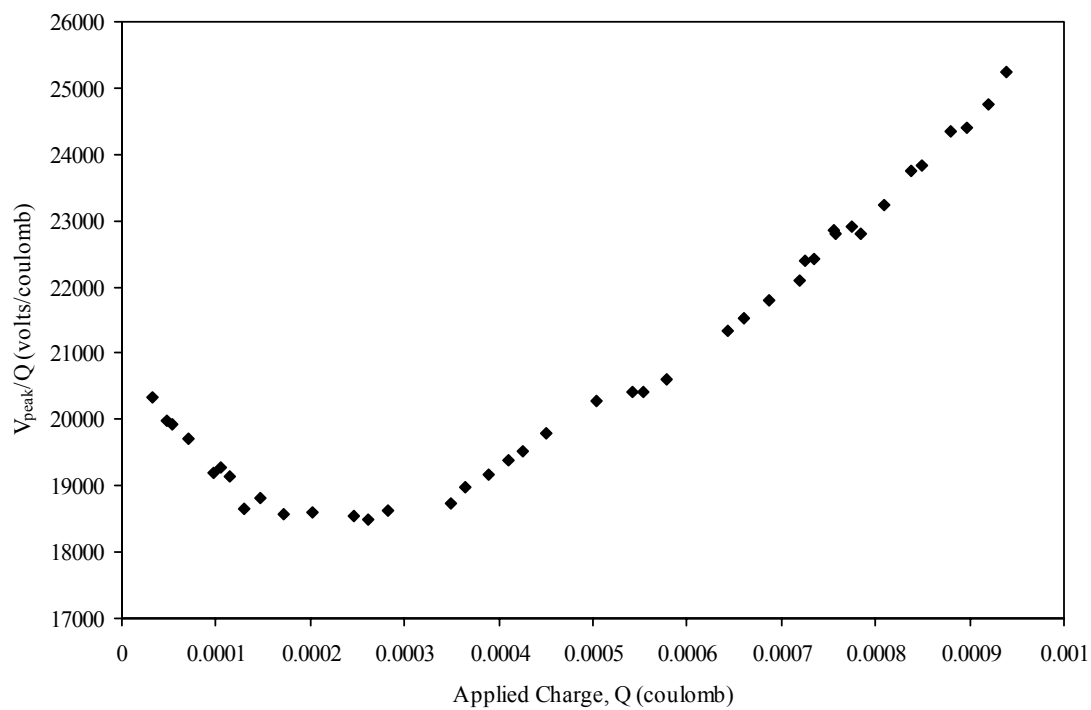
Fig. 7: Peak sense-wire voltage versus applied charge, Q.

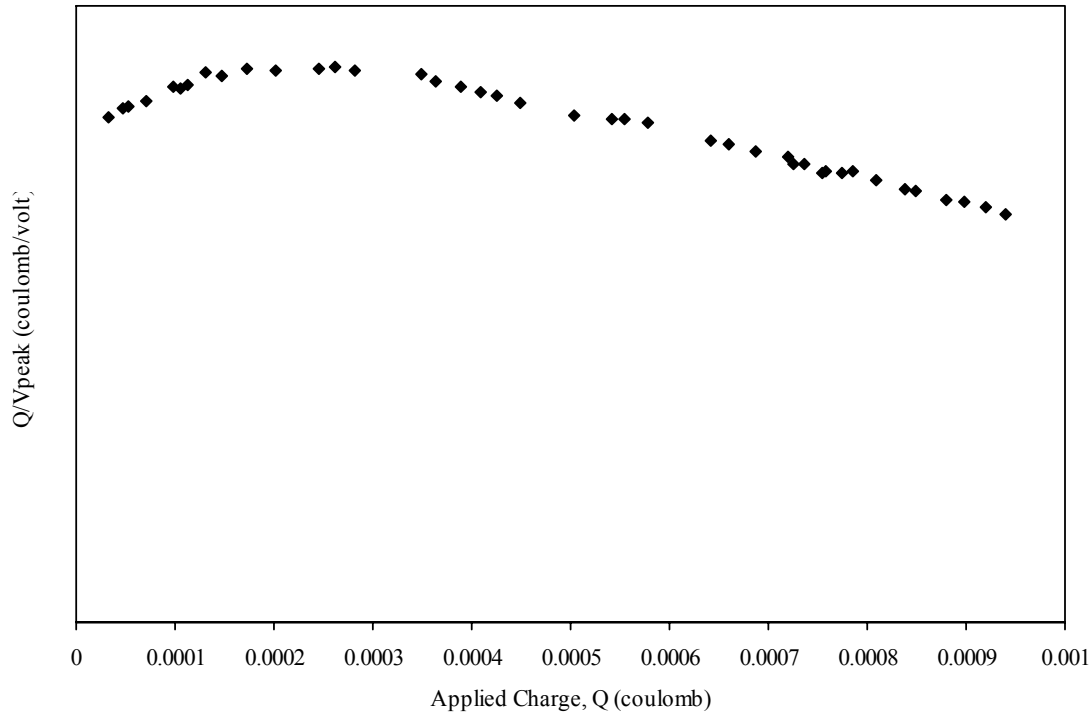Fig. 8: Ratio of peak sense-wire voltage to applied charge Q.

Fig. 9: Ratio of applied charge, Q, to peak sense-wire voltage, V_{peak}.

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